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Identification of the Optimal Value of the *Dithering Tone* Frequency to Mitigate Rayleigh-Backscattering-Induced Distortion in Radioastronomic Scenarios

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Abstract

In the context of the Radio over Fiber downlinks belonging to the Aperture Array Verification System (AAVS) of the low frequency Square Kilometre Array (SKA-LOW) radio telescope, the combination of modulation of the optical carrier by Radio Frequency Interfering Tones (RFIs) and fiber-induced Rayleigh Backscattering (RBS) determines the presence of undesired spurious frequency terms.

A successful countermeasure to the phenomenon has been proposed, based on the additional modulation with a low frequency tone (called *dithering tone*) which mitigates such distortions exploiting the laser chirp effect.

In the present work, through a rigorous theoretical and experimental study, the optimal design parameters of such solution are put into evidence, showing that an appropriate choice of the *dithering tone* frequency allows to reduce to acceptable levels the RBS induced nonlinearities, while minimizing the power consumption of the corresponding introduced devices.

1 Introduction

When the Radio over Fiber (RoF) technology is utilized for the realization of Antenna downlinks within Radioastronomic scenarios, the low levels of both power and coherence of the signals coming from sky sources and traveling into the optical fiber practically impedes spurious frequencies generations due to nonlinear effects associated to the optical link of the system.

On the contrary, the unavoidable Radio Frequency Interference signals (RFIs), resulting, for example, from high power FM transmitters and/or artificial satellites and/or radio and television signals, can exhibit sufficient levels of both power and coherence to give rise to the above-mentioned phenomenon. While the presence of RFIs at the receiving end can be predicted and kept under control, the presence of these associated undesired spurious frequency terms contaminates a portion of the spectrum that would otherwise be free, thus limiting the sensitivity of the radio telescope, then, for this reason, they must be reduced to negligible levels.

One important mechanism of generation of such frequency terms, considering RoF systems based on single mode fibers of G.652 type and operating in the second optical window (wavelength $\lambda \sim 1310 nm$), results from the fact that a small portion of the RFI-modulated optical signal, after having been backscattered by Rayleigh effect, acts as a feedback signal inside the laser cavity, interacting with the optical signal presently generated [1].

An effective solution to reduce to acceptable levels the described nonlinear effects consists in performing an additional modulation of the optical transmitter via a sinusoidal current $I_{DT}(t)$ (named also *dithering tone*) given by

$$I_{DT}(t) = I_{dith} \cos(2\pi f_{dith} t) \qquad (1)$$

where I_{dith} is its amplitude and f_{dith} its frequency. This operation, exploiting the resulting chirp effect of the laser source, reduces indeed the interaction between the present optical signal and its backscattered delayed version [2-3]. This solution, which has been successfully utilized in the past to reduce interferometric noise in optical fiber systems [4], has recently been implemented in all the RoF downlinks of the Aperture Array Verification System (AAVS2) of the low frequency Square Kilometre Array (SKA-LOW) radio telescope.

In [5] a detailed investigation on theoretical and experimental aspects of the *dithering tone* countermeasure was performed, which allowed to identify the value of I_{dith} able to keep below a certain level both the spurious terms at multiple frequencies of the RFI tone, as well as those at the frequency of the *dithering tone* itself summed or subtracted to the one of the RFI tone. The study was performed assuming for f_{dith} a constant value $f_{dith} = 10KHz$.

However, it would be of interest to determine how these optimal values of I_{dith} change as a function of f_{dith} . This would indeed permit to find the most appropriate solution to the problem described, in which the reduction to acceptable levels of the undesired spurious frequency terms is obtained with the smallest possible values of I_{dith}, i.e., of the power consumption of the *dithering tone* countermeasure.

In the present work, a theoretical and experimental investigation activity will be illustrated, which leads to the determination of the optimal value of the frequency f_{dith} of the *dithering tone*. Utilizing such value/values of f_{dith}, the reduction to acceptable levels of the detrimental effects due to Rayleigh Backscattering induced nonlinearities in

Radio over Fiber systems for Radioastronomic applications will be obtained maintaining at the same time the power consumption of the *dithering tone* at the minimal possible levels.

In the following, the analysis will be focalized on the minimization of the undesired 2nd harmonic product of the RFI tone. However, the considerations developed have a general validity, and can therefore be applied to find the value of f_{dith}, which allows to reduce all the above mentioned spurious harmonic and intermodulation distortion terms while keeping I_{dith} at its lowest possible value..

2 Experimental Results

Fig.1 represents one of the RoF downlinks of the AAVS antennas, together with its emulation performed in the laboratory.

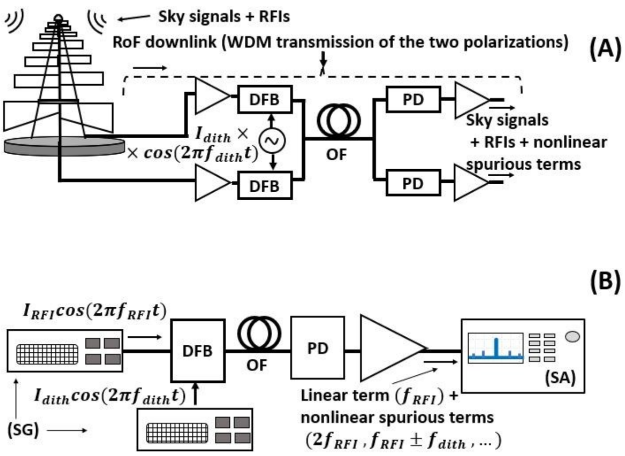

Figure 1. (A) Schematic representation of a RoF downlink of AAVS1; (B) Laboratory setup utilized, emulating the downlink of one of the two field polarizations received by the antenna. DFB: Distributed Feedback Laser; OF: Optical Fiber; PD: Photodiode; SG: Signal Generator; SA: Spectrum Analyzer. See text for details.

The system characterized in the experimental setup, which is represented in Fig. 1(B), consisted in a directly modulated 1310nm DFB laser emitting +6dBm of optical power, followed by 10Km of G.652 Standard Single Mode Fiber and ending in a PIN photodiode, after which a 20dB post amplification was performed.

A first experimental characterization has been performed considering an RFI tone of frequency $f_{RFI} = 70MHz$ and measuring the behavior of the second harmonic spurious term generated at frequency $f = 2f_{RFI} = 140MHz$, named $HD2_{70MHz}$.The input power of the RFI in the laser was set to the realistic value of -26dBm.

This condition represents a case example of the peculiar combination of RFI's frequency and power which produces a high-power level of the RFI harmonics. As shown in [3,5] this analysis could be generally extended to any RFI frequency.

In Figure 2 the results obtained varying the dithering frequency in the KHz range are presented with respect to the value of dithering current injected. It can be noted that an increase of the dithering frequency causes a decrease of the second harmonic spurious term.

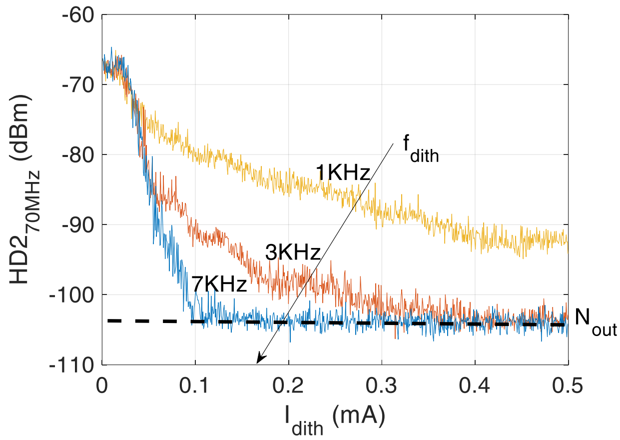

Figure 2. Behavior of $HD2_{70MHz}$ vs. dithering current for different value of f_{dith} ranging from 1KHz to 7KHz.See text for details.

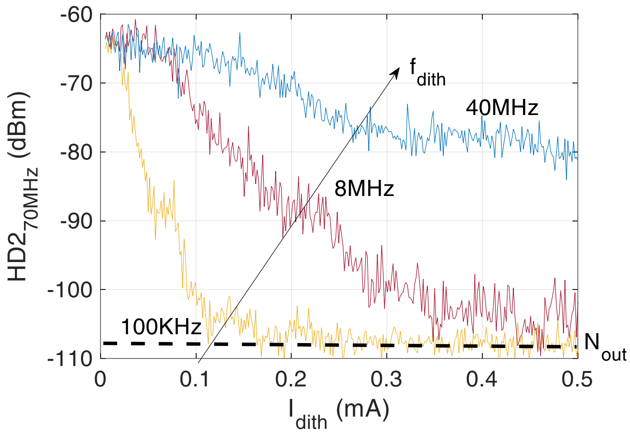

Figure 3. Behavior of $HD2_{70MHz}$ vs. dithering current I_{dith} for different value of f_{dith} ranging from 100KHz to 40MHz. See text for details.

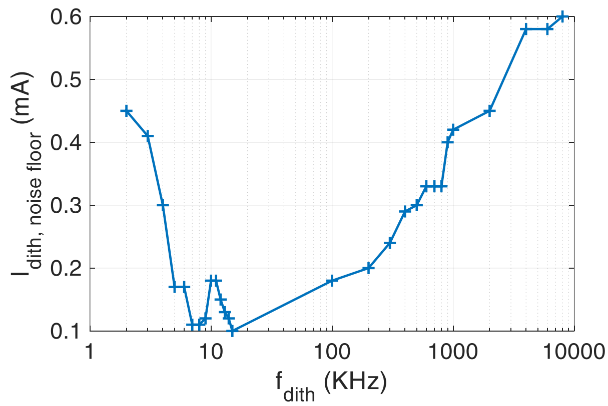

Figure 4 Values of I_{dith} which determine $HD2_{70MHz}$ to reach the noise floor, for different values of f_{dith} ranging from 2KHz to 8MHz.

On the contrary, looking at the experimental results reported in Figure 3, which considers a range of higher values of dithering frequencies, in the hundreds of KHz to tens of MHz range, the trend appears as opposite. Indeed, an increase of f_{dith} determines an increase of $HD2_{70MHz}$ as well.

This means that, fixing the maximum acceptable level for $HD2_{70MHz}$ coincident e.g. with the noise floor N_{OUT} (see again Figures 2 and 3), the dithering frequencies to choose in order to minimize $HD2_{70MHz}$ as well as the *dithering tone* amplitude I_{dith} fall in the interval approximately given by $f_{dith} \in [5KHz, 10KHz]$ (see Figure 4).

3 Theoretical model explaining the observed behaviors

According to the model derived in [5], which is not reported in detail for the sake of brevity, the behaviors of $HD2_{70MHz}$ reported in Figures 1 and 2 should be proportional to the function

$$HD2 \propto \sum_k J_0^2\left(2\frac{K_f \cdot I_{dith}}{f_{dith}}\sin\left(\frac{2\pi f_{dith} z_k}{v_g}\right)\right) = \sum_k J_0^2\left(2M_{dith}\sin\left(\frac{2\pi f_{dith} z_k}{v_g}\right)\right) = g(M_{dith}) \quad (2)$$

where K_f is the adiabatic chirp coefficient of the laser (which in [5] is considered weakly varying with f_{dith}), and v_g is the group velocity of the signal in the optical fiber.
The quantity z_k is the coordinate of the generic k-th fiber section where a portion of the propagating field is backscattered due to the Rayleigh effect. In (2) it has also been introduced the phase modulation index (PMI) referred to the dithering tone $M_{dith} = \frac{K_f(f_{dith}) \cdot I_{dith}}{f_{dith}}$ [6].
Eq. (2) can be however employed knowing that, especially at low frequencies, the value of PMI is highly influenced by the feedback produced by RBS into the laser.
This effect can be described as a generalization of the single self-reflection feedback model proposed by Kobayashi-Lang [7]. In particular, in [8] it is shown that the PMI is modified because of the feedback, with a behavior which depends also on the modulating frequency. The result obtained in [8] for a single reflection can then be extended to the presence of multiple reflections generated by RBS. In particular, a new value of the PMI, named $M_{dith,new}$, can be obtained by the following relation:

$$M_{dith,new} = \frac{M_{dith}}{\left|1 - j\sum_k (1 - e^{-j\theta_k})\frac{C_k}{\omega_{dith}}\sqrt{1+\alpha_H^2}\,\frac{2J_1(X_k)}{X_k}\right|} \quad (3)$$

where M_{dith} represents the PMI in absence of feedback, α_H is the linewidth enhancement factor, θ_k is an aleatory phase generated at the section z_k by RBS and uniformly distributed between $-\pi$ and π , $X_k = 2M_{dith,new}\sin\left(\frac{\omega_{dith} z_k}{v_g}\right)$ and C_k , generalizing the definition reported in [7], is a coupling factor defined as follows:

$$C_k = \frac{C_e}{\sqrt{\gamma}}\frac{\rho_k}{\tau_L}e^{-\alpha z_k} \quad (4)$$

where C_e is the laser-fiber coupling factor, γ is the amount of isolation given by the opto-isolator installed in the laser, which in our case is about 30dB, τ_L is the round-trip time in the laser cavity, typically around 3.3ps, ρ_k is the Rayleigh scattering coefficient at the k-th section and α is the attenuation coefficient of the fiber which at 1310nm is about $10^{-4} neper/m$.

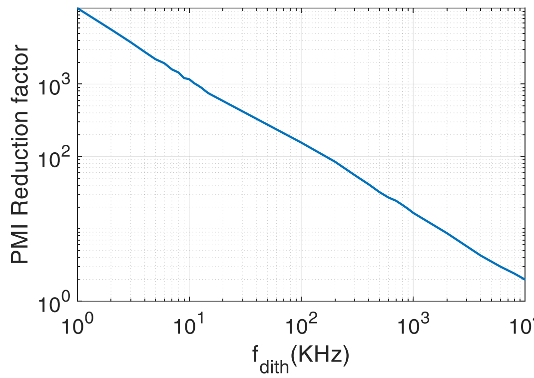

Figure 5 PMI reduction factor computed from Eq (3). See text for details.

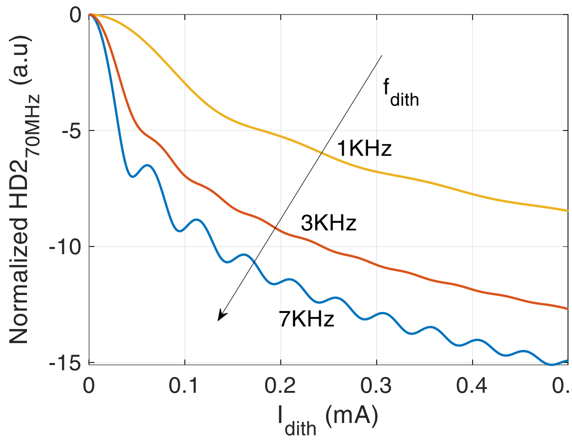

Figure 6 Simulated behavior of $HD2_{70MHz}$ vs. dithering current I_{dith} for different value of f_{dith} ranging from 1KHz to 7KHz. See text for details.

Evaluating Eq. (2) it is possible to observe that the feedback impacts significantly at lower frequency on the PMI, changing drastically its value. Figure 5 shows the PMI reduction factor defined as $M_{dith}/M_{dith,new}$ where it is possible to observed how the lower frequencies are much more subject to change (reduction) of the PMI compared to the higher ones.
After the evaluation of $M_{dith,new}$ by Eq (3), the behavior of HD2 can be computed from Eq. (2) as $g(M_{dith,new})$.

Figures 6, 7 and 8 show the modelled behavior corresponding to the experimental ones shown in Figures 2,3 and 4, respectively.

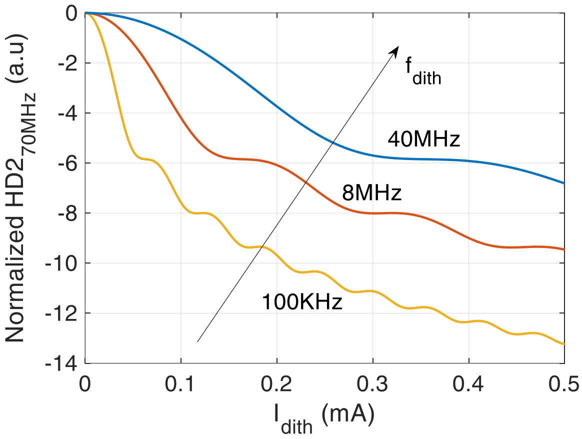

Figure 7 Simulated behavior of I_{dith} which determine $HD2_{70MHz}$ to reach the noise floor, for different values of f_{dith} ranging from 2KHz to 8MHz.

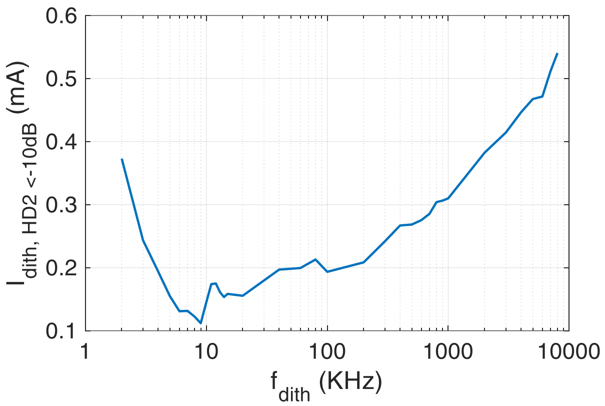

Figure 8 Simulated values of I_{dith} which determine the normalized $HD2$ simulated to reach values lower than-10dB for different values of f_{dith}, ranging from 2KHz to 8MHz.

It is possible to appreciate that the model used describes quite well the behaviors of HD2. In particular, Figure 8 is a further confirmation of the presence of an optimum region of frequencies, ranging from 5KHz to 10KHz, where the value of dithering current employed is minimum.

4 Conclusions

With reference to Radio-over-Fiber-(RoF) based downlinks of radioastronomic antennas which adopt the *dithering tone* technique to minimize the impact of spurious frequency terms caused by Rayleigh Backscattering, the existence of an optimal value of the frequency f_{dith} to be assigned to such *dithering tone* has been evidenced.

Indeed, a thorough experimental and theoretical investigation allowed to show that the value of the *dithering tone* amplitude I_{dith} which guarantees the reduction to acceptable values of the mentioned spurious terms assumes a well identifiable minimum value in correspondence to a limited range of values of f_{dith}.

Utilizing such values of amplitude and frequency, important reductions in total power consumption can be attained, particularly in those applications (e.g. AAVS, SKA1-LOW) where a large number of RoF downlinks is present.

7 References

1. J. Nanni et al., “Challenges due to Rayleigh backscattering in radio over fibre links for the square kilometre array radio-telescope,” in *Proc. 21st Int. Conf. Transparent Opt. Netw.,* Jul. 2019, pp. 1–4.

2. J. Nanni et al., “Optimum mitigation of distortion induced by Rayleigh backscattering in radio-over-fiber links for the square kilometer array radio-telescope,” in *Proc. Int. Topical Meeting Microw. Photon*., Oct. 2019, pp. 1–4.

3. A. Giovannini et al., "Modellization and Control of Spurious Frequency Generation due to Rayleigh Backscattering in Low-Frequency-Radio over Fiber Systems for Radioastronomic Application*," XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science*, Rome, Italy, 2020, pp. 1-4.

4. P. K. Pepeljugoski and K. Y. Lau, “Interferometric noise reduction in fiberoptic links by superposition of high frequency modulation,” *J. Lightw. Technol*., vol. 10, no. 7, pp. 957–963, Jul. 1992.

5. J. Nanni et al., "Controlling Rayleigh-Backscattering-Induced Distortion in Radio Over Fiber Systems for Radioastronomic Applications," in *J. Lightw. Technol.*, vol. 38, no. 19, pp. 5393-5405, 1 Oct.1, 2020.

6. J. Nanni, M. Barbiroli, F. Fuschini, D. Masotti, J.L Polleux, C. Algani, and G. Tartarini, "Chirp evaluation of semiconductor DFB lasers through a simple Interferometry-Based (IB) technique," Appl. Opt. **55**, 7788-7795 (2016)

7. R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," in IEEE Journal of Quantum Electronics, vol. 16, no. 3, pp. 347-355, March 1980.

8. J. Helms and K. Petermann, "Microwave modulation of laser diodes with optical feedback," in Journal of Lightwave Technology, vol. 9, no. 4, pp. 468-476, April 1991.